EXport Processes in the Ocean from RemoTe Sensing (EXPORTS): A Science Plan for a NASA Field Campaign

Submitted by the EXPORTS Science Plan Writing Team
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Executive Summary

The goal of the EXPORTS field campaign *is to develop a predictive understanding of the export and fate of global ocean primary production and its implications for the Earth's carbon cycle in present and future climates.*

NASA's satellite ocean-color data record has revolutionized our understanding of global marine systems by providing synoptic and repeated global observations of phytoplankton stocks and rates of primary production. EXPORTS is designed to advance the utility of NASA ocean color assets to predict how changes in ocean primary production will impact the global carbon cycle. EXPORTS will create a predictive understanding of both the export of organic carbon from the well-lit, upper ocean (or euphotic zone) and its fate in the underlying "twilight zone" (depths of 500 m or more) where a variable fraction of that exported organic carbon is respired back to CO_2. Ultimately, it is this deep organic carbon transport and its sequestration that defines the impact of ocean biota on atmospheric CO_2 levels and hence climate.

EXPORTS will generate a new, detailed understanding of ocean carbon transport processes and pathways linking phytoplankton primary production within the euphotic zone to the export and fate of produced organic matter in the underlying twilight zone using a combination of field campaigns, remote sensing and numerical modeling. NASA's upcoming advanced ocean measurement mission, PACE, will be aimed at quantifying carbon cycle processes far beyond today's ocean color retrievals of phytoplankton pigment concentrations, optical properties and primary production rates. The overarching objective for EXPORTS is to ensure the success of these future satellite mission goals by establishing *mechanistic* relationships between remotely sensed signals and carbon cycle processes. Through a process-oriented approach, EXPORTS will foster new insights on ocean carbon cycling that will maximize its societal relevance and be a key component in the U.S. investment to understand Earth as an integrated system.

Understanding the Roles of Ocean Biota in the Global Carbon Cycle:

Ocean ecosystems play a critical role in the Earth's carbon cycle through net primary production (NPP) processes that fix dissolved CO_2 into organic matter in the well-lit, surface ocean as well as via the combination of ocean food web and oceanographic processes that lead to the vertical transport of this fixed organic carbon to the ocean's interior, where it is sequestered from the atmosphere on time scales of months to millennia. These coupled ocean ecological processes are referred to here as the biological pump (Figure E1).

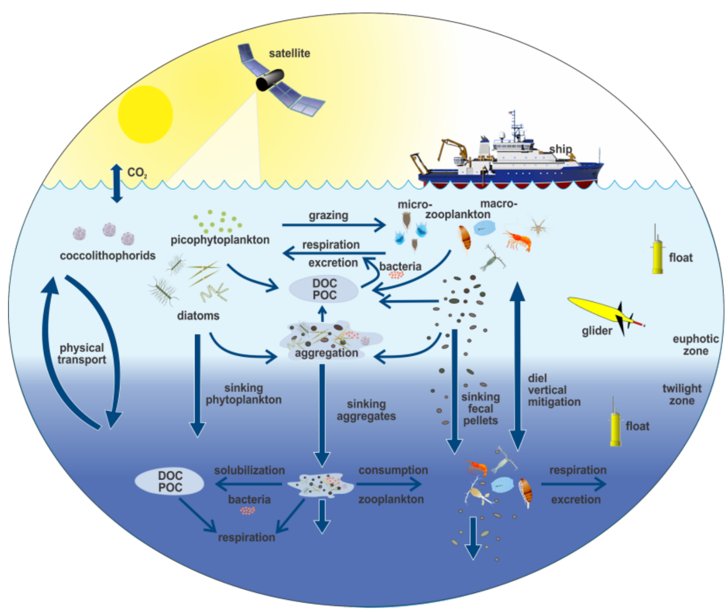

Figure E1 *– Illustration of processes controlling the fates of fixed carbon in the ocean's biological carbon pump.*

The spatial and temporal variations in upper ocean food web structure and circulation alter the efficiency of ocean carbon sequestration. Only a fraction of the organic matter formed in the upper ocean is exported from the surface ocean to deeper waters, where its sequestration depends on both the magnitude of the export flux and where that exported organic carbon is respired in the water column. Carbon can flow through different pathways in ocean food webs, with different efficiencies that lead to variations in carbon export and vertical transport.

Our present ability to quantify the export and fate of ocean NPP from satellite observations or to predict future fates using Earth system models is limited. In fact, current estimates of global carbon export flux from the well-lit surface ocean range from 5 to >12 Pg C yr^{-1}, an uncertainty that is as large as the annual perturbations in the global carbon cycle due to human activities. Yet seemingly small changes in the export and fate of NPP carbon can have profound effects on the global carbon cycle. Further, these differences also influence other ecosystem services that the ocean supports (fisheries, biodiversity, etc.).

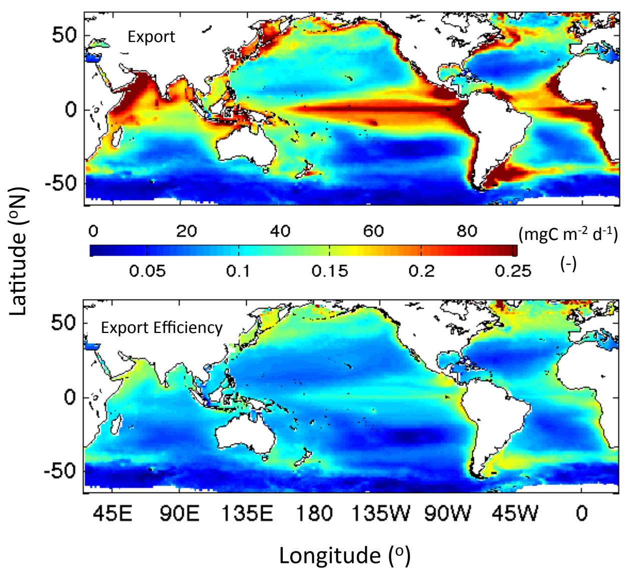

Figure E2: *Determination of (upper) annual export flux from the euphotic zone and (lower) export efficiency (=export/NPP) from Siegel et al. [2014].*

Recent analysis demonstrates that satellite observations of NPP and upper ocean carbon stocks can be combined with food web models to obtain global scale patterns of carbon export and the efficiency that NPP is converted to export flux leaving the upper ocean (Figure E2). Although field determinations of carbon export were used to successfully validate the satellite estimates, the validity of the temporally and spatially fixed food web model used could not be examined because comprehensive oceanographic observations of key mechanisms and fluxes remain unavailable. Planktonic food webs are known to vary both regionally and with environmental conditions making the application of this model to future oceans under different climates highly uncertain. As of this writing, no mechanistic method exists to quantify the long-term fate of upper ocean NPP beneath the surface ocean from satellite observations. And in turn, virtually nothing is known about how these processes may change under future climates.

Quantifying the Export and Fate of Ocean NPP from NASA Satellite Observables: The oceanographic community is excited about NASA's upcoming advanced ocean color mission the Pre-Aerosol Cloud and Ecosystems (PACE) mission. PACE is designed to advance the quality, accuracy and breadth of satellite ocean color data products. Among the novel data products that PACE will retrieve are physiologically-driven models of net primary production, phytoplankton carbon concentration, particle size distributions and phytoplankton community composition - all components for quantifying the export and fate of global ocean NPP.

One of the stated goals for NASA's PACE mission is to quantify the global ocean's carbon cycle providing a new and exciting challenge for the NASA Ocean Biology and Biogeochemistry program. To support PACE, mechanistic satellite algorithms for predicting the export and fate of upper ocean NPP need to be developed, which will in turn require observations of key mechanisms and processes for both algorithm development and validation. Field data of the required type, focus and breadth do not exist presently. The collection, analysis, synthesis and modeling of these observations are objectives of the EXport Processes in the Ocean from RemoTe Sensing (EXPORTS) field campaign.

EXPORTS aims to help provide answers for the penultimate Earth science questions posed in NASA's 2014 Science Plan… "How is the global Earth system changing? What causes these changes in the Earth system? How will the Earth system change in the future? How can Earth system science provide societal benefit?" The EXPORTS Science Plan also addresses NASA Carbon Cycle and Ecosystems Focus Area science questions: "How are global ecosystems changing? How do ecosystems and biogeochemical cycles respond to and affect global environmental change? How will carbon cycle dynamics and marine ecosystems change in the future?" Remote sensing measurements provide the critical link for scaling detailed process study understanding to the regional and global scales required for maximizing societal relevance.

EXPORTS Science Questions: The underlying hypothesis for EXPORTS is that carbon export from the well-lit surface ocean and its fate within the twilight zone can be predicted knowing characteristics of the surface ocean planktonic ecosystem. This approach requires that the fundamental export pathways be quantified; the gravitational settling of particulate organic carbon to depth, the net vertical transport of organic carbon by physical processes (mixing & advection) and carbon transport mediated by the vertical migration of zooplankton (the numbered arrows in Figure E3). The importance of the pathways will vary among ocean provinces and over time. These differences will drive systematic variations in the magnitude of NPP export from the euphotic zone as well as its fate in the twilight zone below.

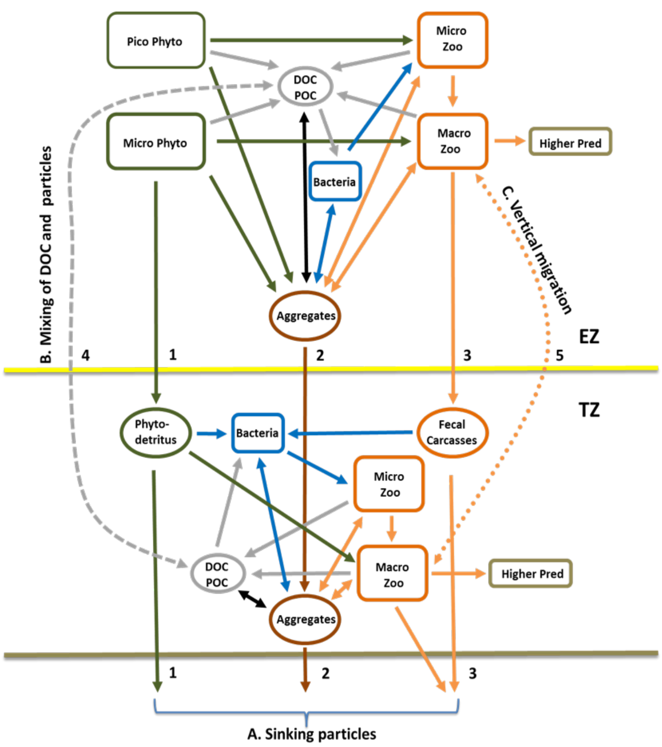

Figure E3 *- Illustration of the pathways regulating the export and the flux of carbon from the euphotic zone (EZ) into the twilight zone (TZ).*

Obtaining a mechanistic understanding of these fundamental export pathways is critical for 1) quantifying the carbon export leaving the well-lit surface layer, 2) assessing the vertical attenuation of that carbon flux below the euphotic zone where it is sequestered on time scales from months to millennia, and 3) predicting these carbon fluxes for present and future oceans. These three points constitute the science questions for the EXPORTS field campaign. EXPORTS will create a comprehensive database capable of answering its science questions as well as creating and validating novel satellite algorithms and numerical models that will quantify the roles of ocean biological processes on present and future states of the ocean's carbon cycle.

EXPORTS Science Plan*:* The EXPORTS science plan integrates ship, autonomous robot and satellite observations of carbon cycling processes with data mining of previous observations and numerical modeling efforts all aimed at improving our predictive understanding of the export and fate of global ocean primary production. The result of the EXPORTS field and data mining program will be a data set that spans the range of states of ocean carbon cycling. The modular nature of the EXPORTS science plan means that the exact location and sequence of field deployments are less important compared with other factors (cf., insuring a wide range of states are observed, logistical simplicity, leveraging existing resources and partnerships, etc.). The modularity of the EXPORTS science plan also makes it easier to schedule field deployments, to de/re-scope the field campaign and to establish partnerships within the U.S. and beyond.

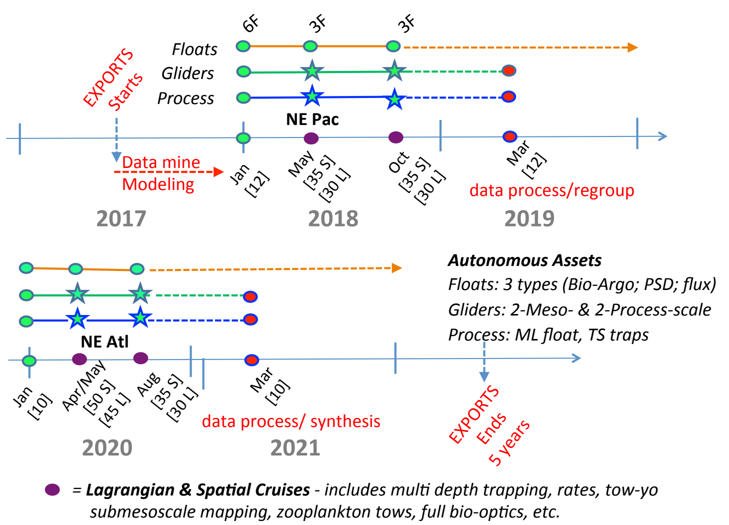

Figure E4 *- Proposed time line for the EXPORTS field campaign. The 5-year field campaign starts in 2017 and ends in 2022. Two major field campaigns with two ships and a pre and post cruise deployment/retrieval cruise are planned in the NE Pacific Ocean (2018) and in the NE Atlantic Ocean (2020). Section 6 discusses the EXPORTS field plan in detail.*

The EXPORTS field program will quantify export pathways during multi-ship field deployments – each designed to observe several ecosystem and carbon cycling states within a 30 to 45 day cruise. Field deployments are planned for the Northeast Pacific (2 cruises to Station P) and the North Atlantic (2 cruises to the NABE site). The sites were chosen because of differences in their food webs structure and the ability to leverage on-going and planned activities (cf., U.S.'s OOI, EU's Horizon 2020, Canada's Line P). The four deployments to two ocean basins and the time needed to analyze and model results, requires EXPORTS to be a 5-year program (Figure E4).

Each field deployment will be conducted in a Lagrangian frame following an instrumented surface float, while spatial distributions of oceanic properties surrounding the float will be resolved using ships, towed instruments, gliders, profiling floats and satellites. This requires two ships; a "Lagrangian" ship that samples the upper 500 m following the instrumented mixed layer float and a "Spatial" ship that makes surveys around the "Lagrangian" ship. With the two research vessels, EXPORTS will sample all of the major export pathways illustrated in Figure E3 as well as supporting physical and optical oceanographic measurements necessary to link measurements back to remotely sensed observables. In particular, the carbon flux leaving the surface ocean and its vertical attenuation with depth will be measured by a host of approaches including drifting sediment trap arrays, biogeochemical and radionuclide budgeting, particle size and sinking rate determinations, and profiling floats.

EXPORTS must sample the appropriate ecological-oceanographic spatial and temporal scales of variability. The "Spatial" ship will be complemented by an array of autonomous gliders and profiling floats providing resolution of properties and processes from local (km's) to regional (100's km's) spatial scales and on synoptic (days) to seasonal (months) time scales. Gliders will be deployed to map out temporally evolving fields of bio-optical and biogeochemical quantities and their sensor outputs will be fully inter-calibrated with ship observations. Profiling floats will provide a long-term (>1 year) view enabling annual export estimates to be made for each study site. Satellite ocean color observations as well as physical oceanographic observations will be used to guide the sampling, interpretation, and modeling of the EXPORTS data set. Finally, ocean optics observations will tie EXPORTS results to NASA's upcoming PACE satellite ocean color measurements through the development of advanced satellite algorithms.

Numerical modeling is central to EXPORTS as prediction is part of EXPORTS' goal statement. Observing System Simulation Experiments (OSSE's) will be used to help plan the multi-scale sampling program while detailed processes models will be developed and employed to understand many factors that are beyond present observational capabilities. These include, but are not limited to, understanding the importance of submesoscale physics on the sequestration of upper ocean NPP energy, the formation and destruction of sinking particle aggregates, and food web models to quantify the significance of species and functional group interactions that regulate the export and fate of upper ocean NPP. Last, coupled Earth system models are needed to quantify the impacts of the EXPORTS discoveries on global scales and to forecast future responses to changes in ocean ecosystems and resulting carbon fluxes.

EXPORTS Implementation*:* A notional implementation plan is provided as part of the EXPORTS science plan and includes suggestions for timeline, technical readiness, data product development and management, project governance, partnership opportunities, and an estimate of resource requirements. Should NASA decide to support EXPORTS, a Science Definition Team will be competed to create a formal Implementation Plan.

EXPORTS Outcomes*:* The goal of EXPORTS is to develop a predictive understanding of the export and fate of global ocean primary production from satellite observations and to improve these predictions into the future. Achieving this goal is among the hardest problems in the Earth Sciences, as it requires a predictive understanding of the combination of ocean ecological, biogeochemical, physical and optical processes. Answering EXPORTS' science questions will accelerate our knowledge of the role of the oceanic food web in the global carbon cycle and provide new models for understanding contemporary and future states of the ocean's carbon cycle and its influences on climate. These results will have tangible societal relevance, leading to advancements in our understanding of our changing planet and reductions in our uncertainties for monitoring its present conditions and for predicting its future state.

EXPORTS will provide answers for many of the NASA Carbon Cycle and Ecosystems Focus Area's science questions while creating the next generation of ocean carbon cycle and ecological satellite algorithms to be used on the upcoming PACE mission. EXPORTS will improve our understanding of global ocean carbon dynamics and reduce uncertainties in our ability to monitor and predict carbon export and its sequestration within the ocean's interior, thus enabling PACE to address its global carbon cycle science objectives. The EXPORTS field campaign will further train and inspire the next generation of interdisciplinary ocean scientists working together on one of the hardest and most important problems in the Earth sciences.

Figure E5 – *The EXPORTS Science Traceability Matrix (STM) tracing the path (from left to right columns) from Science Questions to Approach & Science Plan to Measurements to Requirements.*

Science Questions

1 How do upper ocean ecosystem characteristics determine the vertical transfer of organic matter from the well-lit surface ocean?

2 What controls the efficiency of vertical transfer of organic matter below the well-lit surface ocean?

3 How can the knowledge gained from EXPORTS Be used to reduce uncertainties in contemporary & future estimates of the export and fate of upper ocean net primary production?

Approach (Maps to Science Question)

Approach	Maps to Science Question
A. Use observation system simulation experiment (OSSE) modeling to optimize the design of field studies for addressing EXPORTS science questions	1, 2, 3
B. Characterize ocean net primary production and pathways regulating the fate of this organic carbon during focused field campaigns targeting contrasting ecosystems states.	1, 2
C. Extend ship-based measurement to complete annual coverage of key carbon cycling properties using autonomous sensors	1, 2
D. Data mine results from previous field studies to expand upon the range of ecosystem states directly sampled during EXPORTS	1, 2
E. Link field-observed carbon stocks and regulatory pathways to remotely observable properties and numerical models to allow quantitative assessment of carbon fates from satellite assets.	2, 3
F. Execute data-informed 4-D coupled models to evaluate future changes in the ocean carbon pump	3

Deployment Requirements (Maps to Approach)

Deployment Requirements	Maps to Approach
Conduct four field deployments at two functionally distinct locations	B, E
During each deployment, quantify carbon stocks and rates of organic carbon formation, transport, and transformations from one ship that operating in a 'parcel tracking' (Lagrangian) manner (i.e., following a float)	B
During each deployment, assess biogeochemical and physical properties from a second survey ship operating over an ~100 km scale (centered on the 'parcel tracking' ship) to evaluate meso- to submesoscale variability and to constrain physical pathways for vertical carbon transport	B
Conduct each deployment for sufficient duration to track newly formed organic carbon from the photic zone to a depth of ~500 m	B, E
Deploy autonomous gliders measuring key physical, ecological / biogeochemical proxies to extend spatial sampling (1 km to 100 km)	C
Deploy profiling floats to sustain vertical profiling measurements of key physical, ecological and biogeochemical proxies for periods of > 1 yr	C
Use ships of opportunity to extend measurements of key physical and biogeochemical properties throughout the annual cycle	B

Measurement Requirements (Maps to Science Question / Maps to Approach)

	Measurement Requirements	Maps to Science Question	Maps to Approach
SHIP	*Water column characterization*: hydrography, circulation, optics, nutrients & carbon stocks *Food web structure*: particle size distribution and composition, plankton abundance, community composition, carbon content *Food web function*: net primary production, phytoplankton physiology, heterotrophic respiration & grazing, net community production *Export pathways*: Sinking particle flux, particle aggregation/disaggregation, dissolution & sinking rates, vertical zooplankton migration & associated fluxes and physical vertical carbon fluxes *Above-water optical properties*: 5 nm resolution UV-VIS-NIR remote sensing reflectance spectra (consistent with PACE), lidar-based profiling of water column optical properties structure	1, 2, 3	B, D, E
AUTONOMOUS	*Profiling floats and gliders*: Physical (T, S, u & v), biogeochemistry (O_2, NO_3), & optical proxies for organic carbon, particle size, abundance & type distribution and vertical sinking flux attenuation *Other*: Water-following mixed layer float, Cross-calibration of all sensor data and calibration to in situ data observations	1, 2, 3	B, C, E
SATELLITE	*Satellite retrievals*: Chlorophyll, particulate organic carbon, phytoplankton carbon, colored DOM, net primary production, particle size, sea level height, and SST *Near real time products*: preliminary retrievals of above satellite products for guiding field deployments	1, 2, 3	E, F

Numerical Modeling Requirements

	Numerical Modeling Requirements	Maps to Science Question	Maps to Approach
MODELING	OSSE's for planning field deployments Coupled physical / biogeochemical / ecological modeling at submesoscales for assessing relative export pathways Detailed process modeling (e.g., particle aggregation, etc.) Coupled models for hindcasting & forecasting NPP export states	1, 2, 3	A, E, F

Logistic / Project Requirements

FIELD DEPLOYMENTS

- Two 30+ day campaigns in the Northeast Pacific, performed sequentially: May and then October
- One 45+ and one 30+ day campaign in Northeast Atlantic, performed sequentially in April and then August
- Research vessel with sufficient berthing and seaworthiness
- Profiling float and glider deployment four months prior each campaign
- Characterize key physical and biogeochemical properties across seasonal time-scale at both sites
- Basin-scale satellite retrievals of surface ocean physical properties and ecosystem properties from existing/upcoming satellites

SYNTHESIS & MODELING

- Integration of field measurements into synthetic data products
- Use synthetic data products to build & test numerical models and algorithms
- Coupled Earth system modeling to optimize field campaign design, understand mechanisms of physical-ecosystem-biogeochemical variability, and forecast impacts of changes in ocean biological carbon pump

PROJECT ORGANIZATION

- Centralized project office, field event recording & project data management
- Teams of PI's working to create integrated data products
- Data mining to expand data set breadth
- Open meetings & berth availability to encourage partnerships